



Issues in Neutrino Physics:

Stephen Parke

FermiLab

FermiLab Long Range Neutrino Plan

The Questions:

- **# of Light Neutrinos:** 3 active + ? steriles
- **Majorana v Dirac:** $\nu = \bar{\nu}$, 2 v 4 states per ν , L viol.
- **Masses:** degenerate, normal/inverted, M_{lite}
- **Mixings:** θ_{13} , $\theta_{23} \stackrel{?}{=} \frac{\pi}{4}$, U real v complex, CP viol., Leptogenesis
- **Exotics:** Non-Osc., CPT-V, decays, μ -mom etc

The Questions:

Theorists' Poll

- **# of Light Neutrinos:** 3 active + ? steriles
- **Majorana v Dirac:** $\nu = \bar{\nu}$, 2 v 4 states per ν , L viol.
- **Masses:** degenerate, normal/inverted, M_{lite}
- **Mixings:** θ_{13} , $\theta_{23} \stackrel{?}{=} \frac{\pi}{4}$, U real v complex, CP viol., Leptogenesis
- **Exotics:** Non-Osc., CPT-V, decays, μ -mom etc

The Questions:

Theorists' Poll

- # of Light Neutrinos: Three
- Majorana v Dirac: Majorana
- Masses: Seesaw
- Mixings: ???
- Exotics: None

Addressing these Questions:

- # of Light Neutrinos:

If CPT is conserved,
then directly addressed by mini-BOONE → ??? ← Kayser

- Majorana v Dirac:

$\cancel{\nu\beta\beta}$ Decay
Cosmic Background Neutrinos

- Masses and Mixings:

Tritium, Solar, Atmospheric, Cosmology
Reactors, LBL, SuperLBL ← Link, Feldman, Geer

- Standard Model and Non-SM Interactions:

Near Detectors ← McFarland

Neutrino Mixing Matrix:

Like the Quark Sector:

The Neutrino Mass Eigenstates, $|\nu_i\rangle$, are a Mixture of Flavor States, $|\nu_\alpha\rangle$:
 $|\nu_\alpha\rangle = U_{\alpha i} |\nu_i\rangle$. (using $s_{ij} = \sin \theta_{ij}$ and $c_{ij} = \cos \theta_{ij}$)

$$U_{\alpha i} = \begin{pmatrix} 1 & & \\ c_{23} & s_{23} & \\ -s_{23} & c_{13} & \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

Atmos. L/E $\mu \rightarrow \tau$ Atmos. L/E $\mu \leftrightarrow e$ Solar L/E $e \rightarrow \mu, \tau$

$$= \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

Neutrino Mixing Matrix:

Like the Quark Sector:

The Neutrino Mass Eigenstates, $|\nu_i\rangle$, are a Mixture of Flavor States, $|\nu_\alpha\rangle$:
 $|\nu_\alpha\rangle = U_{\alpha i} |\nu_i\rangle$. (using $s_{ij} = \sin \theta_{ij}$ and $c_{ij} = \cos \theta_{ij}$)

$$U_{\alpha i} = \begin{pmatrix} 1 & & \\ c_{23} & s_{23} & \\ -s_{23} & c_{13} & \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

Atmos. L/E $\mu \rightarrow \tau$ Atmos. L/E $\mu \leftrightarrow e$ Solar L/E $e \rightarrow \mu, \tau$

$$= \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

If Majorana

$$U \rightarrow U \begin{pmatrix} 1 & & \\ & e^{i\alpha_2} & \\ & & e^{i\alpha_3} \end{pmatrix}$$

Phases α_2, α_3 are unobservable in oscillation phenomena, $(U_{\alpha i} U_{\beta i}^*)$.
 Important in neutrinoless double beta decay.

Mixings and Masses Overview:

(12)-Sector: SNO, KamLAND, SK

$$\delta m_{21}^2 = +7.1 \pm 2.0 \times 10^{-5} \text{ eV}^2$$

$$0.23 < \sin^2 \theta_{12} < 0.35$$

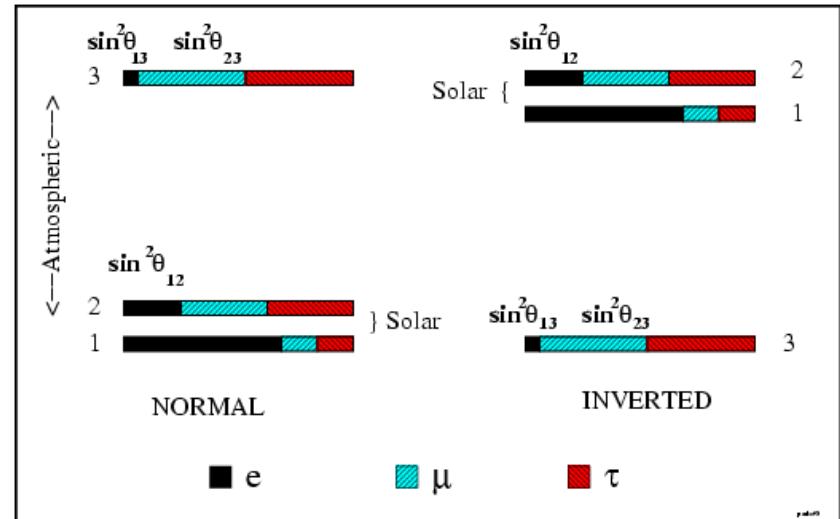
$\sin^2 \theta_{12} \geq \frac{1}{2}$ excluded at $> 5 \sigma$!

Sign of δm_{21}^2 determined at this C.L.

Due to matter effects

the ${}^8\text{B}$ solar neutrinos exit the sun as ν_2 .

Thus SNO's $\frac{CC}{NC} = \sin^2 \theta_{12}$



Consistency between SNO and
KamLAND will be an important test of
Neutrino Oscillations and Matter
Effects.

Mixings and Masses Overview:

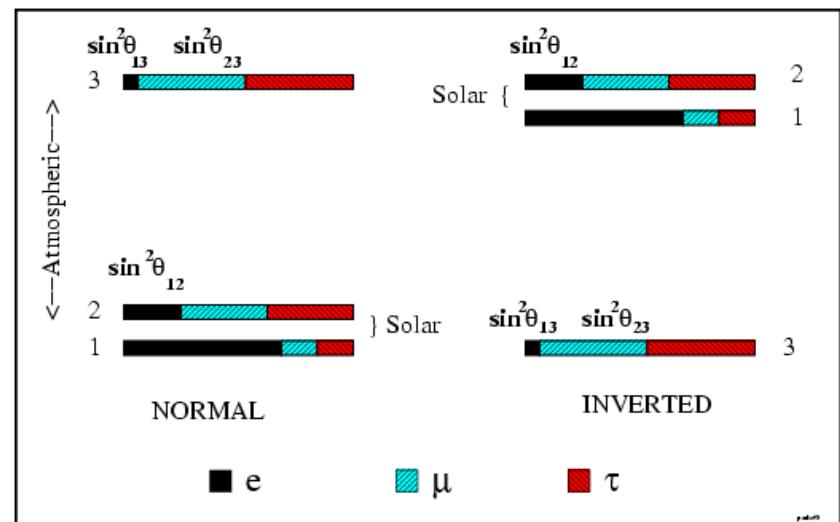
(12)-Sector: SNO, KamLAND, SK

$$\delta m_{21}^2 = +7.1 \pm 2.0 \times 10^{-5} \text{ eV}^2$$

$$0.23 < \sin^2 \theta_{12} < 0.35$$

$\sin^2 \theta_{12} \geq \frac{1}{2}$ excluded at $> 5 \sigma$!

Sign of δm_{21}^2 determined at this C.L.



(23)-Sector: SK, K2K

$$|\delta m_{32}^2| = 1.5 - 3.5 \times 10^{-3} \text{ eV}^2$$

$$0.35 < \sin^2 \theta_{23} < 0.65$$

(obtained from $\sin^2 2\theta_{23} > 0.91$)

Magnitude of δm_{32}^2 and $\sin^2 \theta_{23}$ both poorly known!

Sign of δm_{32}^2 Unknown !!!

\Rightarrow MINOS $|\delta m_{32}^2| \spadesuit$
also tests ν -Oscillations.

Mixings and Masses Overview:

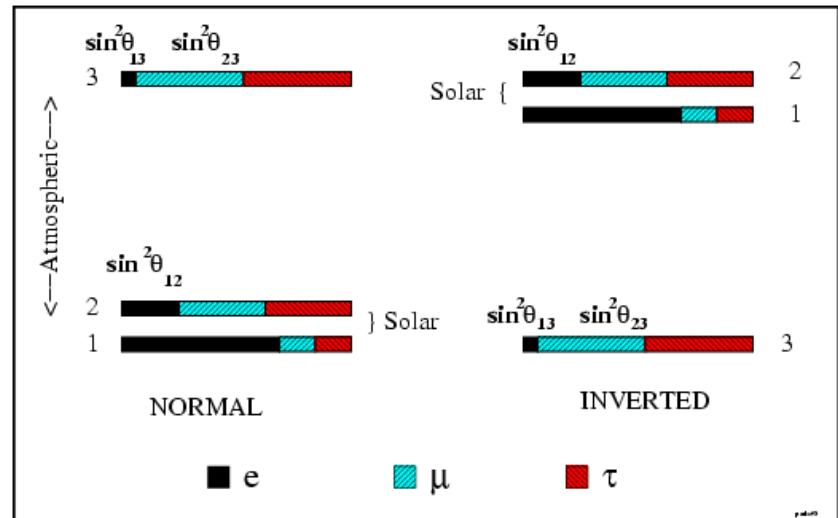
(12)-Sector: SNO, KamLAND, SK

$$\delta m_{21}^2 = +7.1 \pm 2.0 \times 10^{-5} \text{ eV}^2$$

$$0.23 < \sin^2 \theta_{12} < 0.35$$

$\sin^2 \theta_{12} \geq \frac{1}{2}$ excluded at $> 5 \sigma$!

Sign of δm_{21}^2 determined at this C.L.



(23)-Sector: SK, K2K

$$|\delta m_{32}^2| = 1.5 - 3.5 \times 10^{-3} \text{ eV}^2$$

$$0.35 < \sin^2 \theta_{23} < 0.65$$

(obtained from $\sin^2 2\theta_{23} > 0.91$)

Magnitude of δm_{32}^2 and $\sin^2 \theta_{23}$ both poorly known!

Sign of δm_{32}^2 Unknown !!!

(13)-Sector: Chooz, SK, K2K

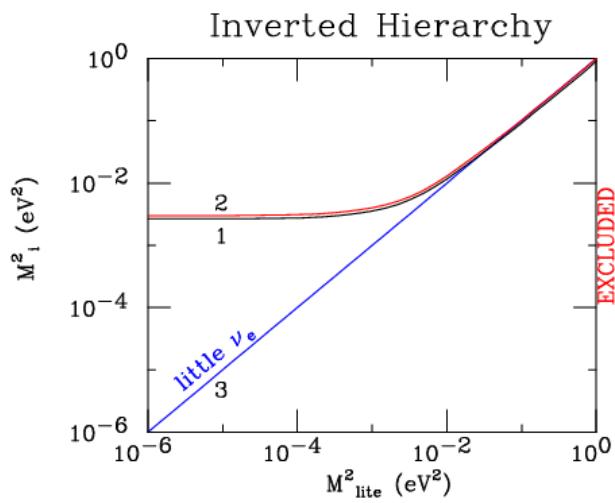
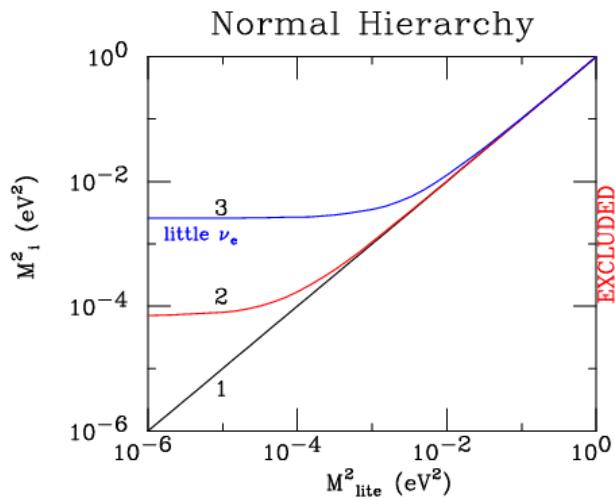
$$\sin^2 \theta_{13} < 0.03 - 0.05$$

limit $|\delta m_{32}^2|$ dependent

$$0 \leq \delta_{CP} < 2\pi$$

Unknown!

Absolute Mass Scale:



- Tritium Decay:
$$\langle m_\beta^2 \rangle = \sum |U_{ei}|^2 m_i^2$$

KATRIN down to 0.3 eV²

- $\cancel{\nu} \beta\beta$ Decay:
$$\langle m_{\beta\beta} \rangle = |\sum U_{ei}^2 m_i|$$

Signal <10 meV excludes inverted.

- Multiple Supernova:

- Cosmology: (C.L. ???)

What about M_{lite} ?

$$\underline{\sin^2 \theta_{13} \ (\ll 1)}$$

Reactors: $P_{e \rightarrow e} = 1 - \sin^2 2\theta_{13} \sin^2 \Delta_{31}$ ← Link
+ tiny terms.

LBL: $P_{\mu \rightarrow e} = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \Delta_{31}$
no matter + not so tiny terms. ← Feldman

SuperLBL: $P_{\mu \rightarrow e} = \sin^2 \theta_{23} \sin^2 2\theta_{13}$
 $\times \left(\frac{\Delta_{31}}{\Delta_{31} \mp aL} \right)^2 \sin^2(\Delta_{31} \mp aL)$ ← Geer
incl. matter + not so tiny terms.

where $\Delta_{31} = \delta m_{31}^2 L / 4E = 1.27 \ \delta m_{31}^2 L / E$

and $a = G_F N_e / \sqrt{2} \approx (4000 \ km)^{-1}$.

$$\underline{\text{sign } \delta m_{32}^2}$$

At Oscillation Maximum , $\Delta_{31} = \frac{\pi}{2}$

$$P_{mat} = \left(1 \pm 2\frac{E}{E_R}\right) P_{vac}$$

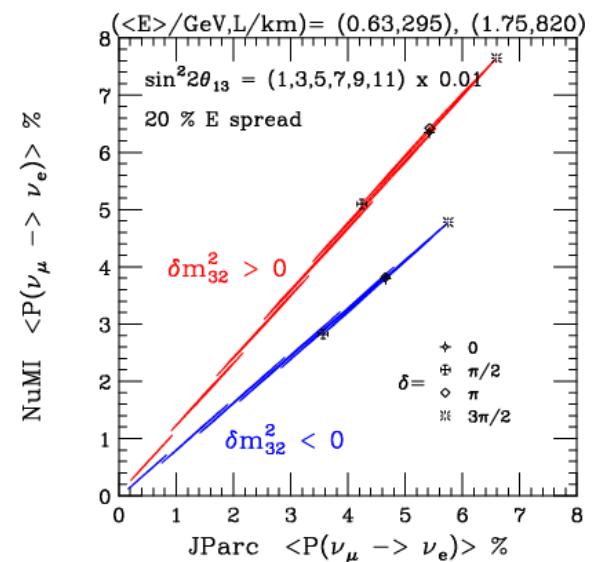
where $E_R \simeq 12$ GeV.

Therefore, if NuMI and JParc both run Neutrinos at Osc. Max.

$$P_{NuMI} = \left(1 \pm 2\frac{(E^N - E^J)}{E_R}\right) P_{JParc}$$

i.e. $P_{NuMI} \approx (1.2 \text{ or } 0.8)P_{JParc}$

Separation degraded for $E^N > E_{OM}$.



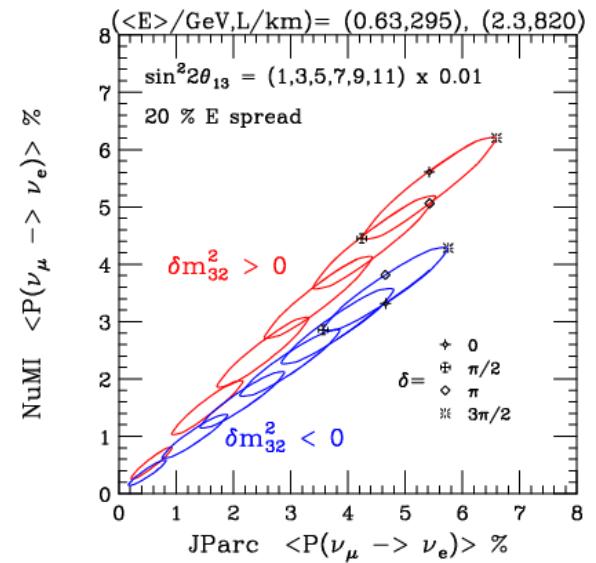
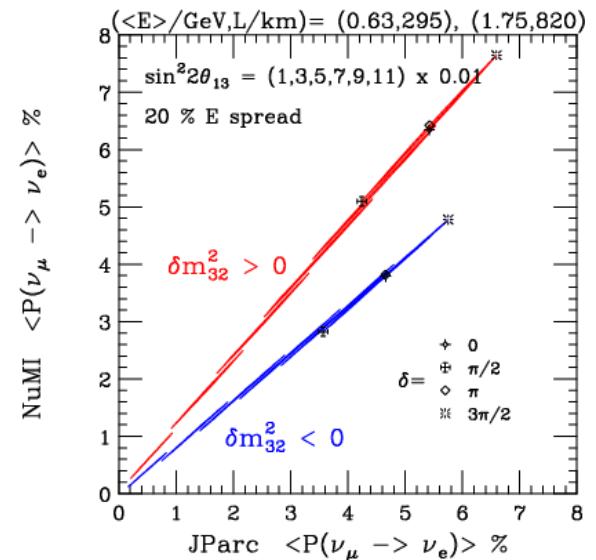
sign δm_{32}^2 conti.

For NuMI above Oscillation Maximum,
 $E = E_{OM} + \Delta E$

$$P_{mat} = \left(1 \pm 2 \frac{E_{OM}}{E_R} \mp \frac{(\pi^2 - 4)}{2} \frac{\Delta E}{E_R} \right) P_{vac}$$

where $E_R \simeq 12$ GeV.

This extra factor $\sim 3 \frac{\Delta E}{E_R}$ degrades the separation of the center of the ellipses.
 Also the ellipses become **FAT**, compare bottom to top figures.

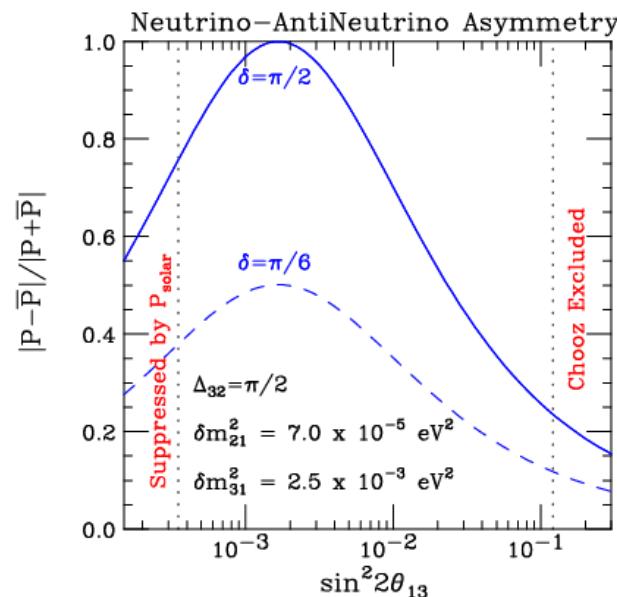


$\sin \delta$ /CP violation/Leptogenesis:

LBL and Super LBL:

Large $\nu - \bar{\nu}$ Asymmetry:

Therefore sensitive to $\sin \delta$.



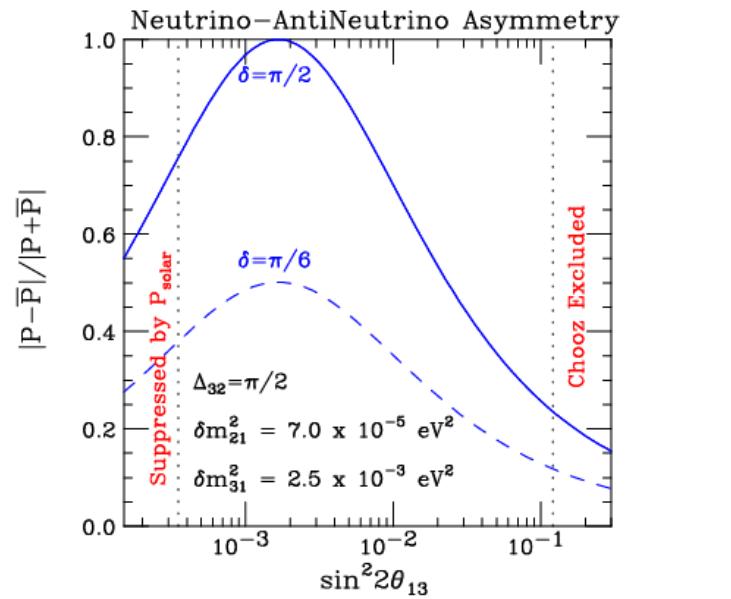
$$\text{Peak at } \sin^2 2\theta_{13} \approx \frac{\sin^2 2\theta_{12}}{\tan^2 \theta_{23}} \left[\frac{\pi}{2} \frac{\delta m_{21}^2}{\delta m_{31}^2} \right]^2$$

$\sin \delta$ /CP violation/Leptogenesis:

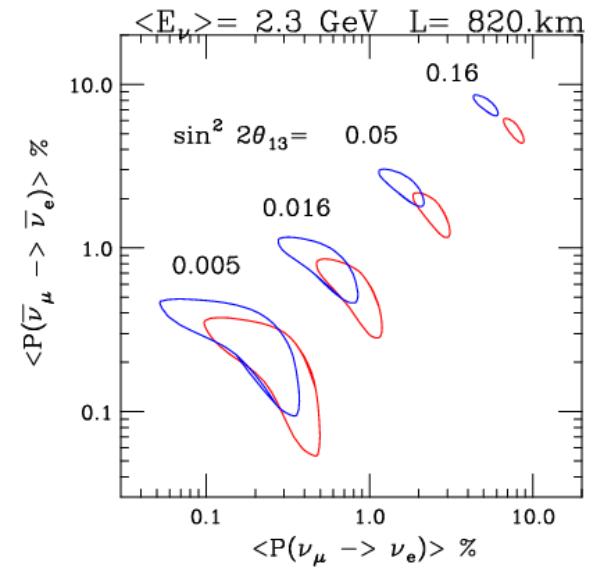
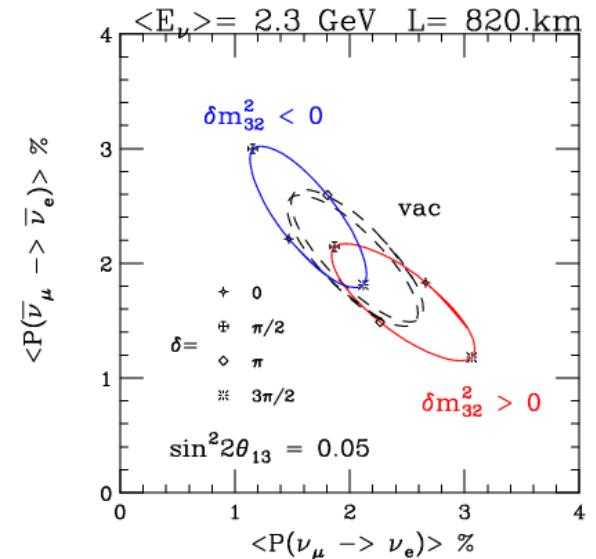
LBL and Super LBL:

Large $\nu - \bar{\nu}$ Asymmetry:

Therefore sensitive to $\sin \delta$.



$$\text{Peak at } \sin^2 2\theta_{13} \approx \frac{\sin^2 2\theta_{12}}{\tan^2 \theta_{23}} \left[\frac{\pi}{2} \frac{\delta m_{21}^2}{\delta m_{31}^2} \right]^2$$



$$\theta_{23} \leftrightarrow \left(\frac{\pi}{2} - \theta_{23}\right)$$

$\theta_{23} = \frac{\pi}{2}$ is $\nu_\mu \leftrightarrow \nu_\tau$ sym. pt.

$\sin^2 2\theta_{23}$ from disapp. exp.

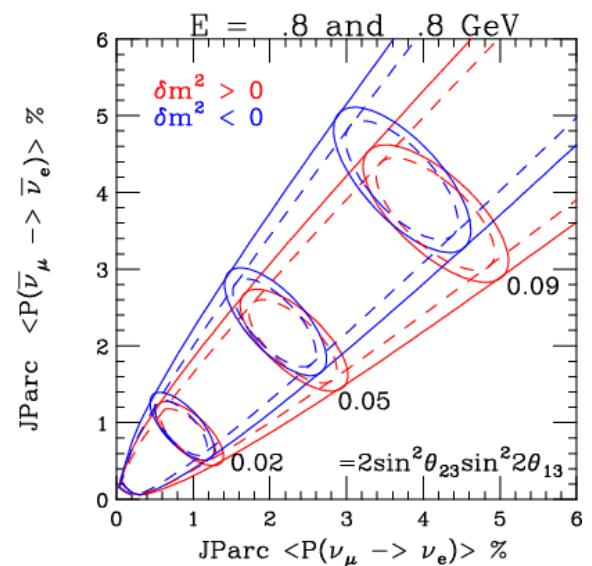
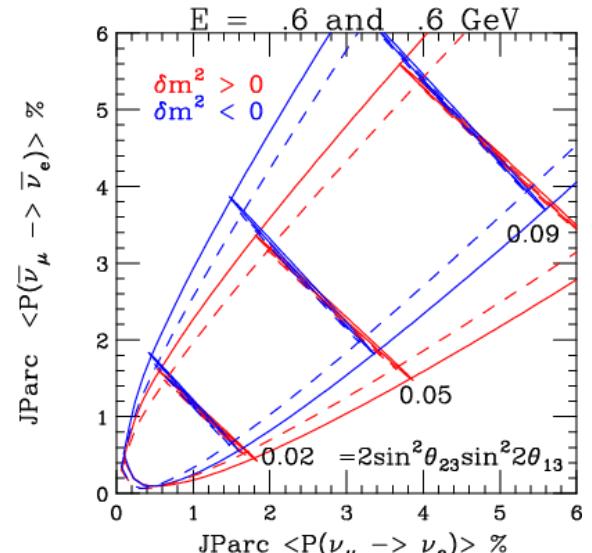
$\sin^2 \theta_{23}$ can be measured by a combination of Reactor and LBL measurements.

$$\underline{\cos \delta}$$

Precision LBL measurement above Osc. Max.

$$\underline{M_{lite}^2}$$

???????????????????



Summary:

- # of Light Neutrinos: **Steriles!!!**
Directly addressed by mini-BOONE → ???
- Majorana v Dirac: **Lepton # Violation!!!**
Need new good ideas!!!
- Masses and Mixings: **size of θ_{13} ,**
 $\theta_{23} \stackrel{?}{=} \frac{\pi}{4}$, Normal/Inverted,
CP Viol./ δ , and Leptogenesis!!!
Reactors, (Super-) Long Baseline, Cosmology.

Experimentalists:

?? SURPRISES ??

?? SURPRISES ??

?? SURPRISES ??

Theorists:

??? MODELS ???

??? MODELS ???

??? MODELS ???